



*Faire avancer la sûreté nucléaire*

# IRSN-ORNL Data Evaluation in Support of Criticality Safety: $^{235}\text{U}$ , $^{239}\text{Pu}$ , $^{56}\text{Fe}$ , $^{16}\text{O}$ , $^{54}\text{Fe}$ , $^{103}\text{Rh}$

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# OUTLINE

1. IRSN-NCSP collaboration organization for nuclear data evaluation work;
2. Evaluations: General description and highlights;
3. IRSN and ORNL collaboration results end perspectives;
4. Concluding remarks;

## Nuclear Data

| <b>Priority Needs / Additional Needs</b>  |  |            | Thermal scattering (BeO, HF, D <sub>2</sub> O, SiO <sub>2</sub> , CH <sub>2</sub> , C <sub>2</sub> F <sub>4</sub> , C <sub>5</sub> O <sub>2</sub> H <sub>8</sub> , etc.), <sup>239</sup> Pu, Cr, <sup>237</sup> Np, Pb, <sup>55</sup> Mn, Ti, <sup>240</sup> Pu / <sup>233</sup> U, Th, Be, <sup>51</sup> V, Zr, F, K, Ca, Mo, Na, La |        |        |        |        |           |        |             |
|---|--|------------|---|--------|--------|--------|--------|-----------|--------|-------------|
| <b>Completed Evaluations (FY)</b>   |  |            | Minor Actinides (13), SiO <sub>2</sub> (12), <sup>55</sup> Mn (12), <sup>180,128,183,184,186</sup> W (10)   |        |        |        |        |           |        |             |
|   | <i>Materials</i>                                       | Pre FY2014 | FY2014  | FY2015 | FY2016 | FY2017 | FY2018 | FY2019    | FY2020 | Post-FY2020 |
| <i>Measurements</i>   | Calcium (Ca)   |            |   |        |        |        |        |           |        |             |
|   | Cerium (Ce)  |            |   |        |        |        |        |           |        |             |
|   | Copper (Cu)  |            |   |        |        |        |        |           |        |             |
|   | Iron (Fe)  |            |   |        |        |        |        |           |        |             |
|   | Lucite (C <sub>5</sub> O <sub>2</sub> H <sub>8</sub> ) |            |   |        |        |        |        |           |        |             |
|   | Strontium (Sr)   |            |   |        |        |        |        |           |        |             |
|   | Tungsten (W)   |            |   |        |        |        |        |           |        |             |
|   | Vanadium (V)   |            |   |        |        |        |        |           |        |             |
|   | Zirconium (Zr)   |            |   |        |        |        |        |           |        |             |
|   | Polyethylene (CH <sub>2</sub> )                        |            |   |        |        |        |        |           |        |             |
|   | <i>Materials</i>                                       | Pre FY2014 | FY2014  | FY2015 | FY2016 | FY2017 | FY2018 | FY2019    | FY2020 | Post-FY2020 |
| <i>Complete Evaluations</i>   | Calcium (Ca)   |            |   |        |        |        |        |           |        |             |
|   | Cerium (Ce)  |            |   |        |        |        |        |           |        |             |
|   | Cobalt (Co)  |            |   |        |        |        |        |           |        |             |
|   | Copper (Cu)  |            |   |        |        |        |        |           |        |             |
|   | Dysprosium (Dy)  |            |   |        |        |        |        |           |        |             |
|   | Gadolinium (Gd)  |            |   |        |        |        |        |           |        |             |
|   | Iron (Fe)  |            |   |        |        |        |        |           |        |             |
|   | Lead (Pb)  |            |   |        |        |        |        |           |        |             |
|   | Nickel (Ni)  |            |   |        |        |        |        |           |        |             |
|   | Oxygen (O)   |            |   |        |        |        |        |           |        |             |
|   | Rhodium (Rh)   |            |   |        |        |        |        |           |        |             |
|   | Plutonium-239  |            |   |        |        |        |        |           |        |             |
|   | Strontium (Sr)   |            |   |        |        |        |        |           |        |             |
|   | Tungsten (W)   |            |   |        |        |        |        |           |        |             |
|   | Uranium-235  |            |   |        |        |        |        |           |        |             |
|   | Uranium-238  |            |   |        |        |        |        |           |        |             |
|   | Vanadium (V)   |            |   |        |        |        |        |           |        |             |
|   | Zirconium (Zr)   |            |   |        |        |        |        |           |        |             |
|   | Hydrofluoric Acid (HF)                                 |            |   |        |        |        |        |           |        |             |
|   | Lucite (C <sub>5</sub> O <sub>2</sub> H <sub>8</sub> ) |            |   |        |        |        |        |           |        |             |
|   | Polyethylene (CH <sub>2</sub> )                        |            |   |        |        |        |        |           |        |             |
|   |  | ORNL       |   | RPI    |        | LANL   |        | LLNL/NCSU |        |             |
| <ul style="list-style-type: none"> <li>• Requests for additional IE measurements: Ni, Mo, Cr (Fe-Cr alloys), Mn in intermediate energy range (VNIITF, NCERC).</li> <li>• Request for measurements and evaluation of angular distributions at high energy for Cu.</li> <li>• Continuing need for thermal scattering data.</li> </ul> |  |            |   |        |        |        |        |           |        |             |

# IRSN-ORNL Tasks

| ISOTOPE           | ABUNDANCE % | THERMAL (barns)  | LAB  |
|-------------------|-------------|------------------|------|
| $^{152}\text{Gd}$ | 0.2         | $735 \pm 20$     | ORNL |
| $^{154}\text{Gd}$ | 2.15        | $85 \pm 12$      | ORNL |
| $^{155}\text{Gd}$ | 14.73       | $60900 \pm 500$  | IRSN |
| $^{156}\text{Gd}$ | 20.47       | $1.8 \pm 0.7$    | ORNL |
| $^{157}\text{Gd}$ | 15.68       | $254000 \pm 815$ | IRSN |
| $^{158}\text{Gd}$ | 24.87       | $2.2 \pm 0.2$    | ORNL |
| $^{160}\text{Gd}$ | 21.9        | $1.4 \pm 0.3$    | ORNL |

# IRSN-ORNL Tasks

| ISOTOPE          | ABUNDANCE % | THERMAL (barns)     | LAB  |
|------------------|-------------|---------------------|------|
| $^{90}\text{Zr}$ | 51.45       | $0.077 \pm 0.016$   | IRSN |
| $^{91}\text{Zr}$ | 11.22       | $0.83 \pm 0.08$     | ORNL |
| $^{92}\text{Zr}$ | 17.15       | $0.260 \pm 0.080$   | IRSN |
| $^{94}\text{Zr}$ | 17.38       | $0.0494 \pm 0.0017$ | ORNL |

# IRSN-ORNL Tasks

■ ORNL staff member visit to IRSN (V. Sobes)

■ Work performed:

- Finalization of the resonance evaluation for  $^{63}\text{Cu}$  and  $^{65}\text{Cu}$ ;
- Development of a new approach to represent angular data in ENDF (ANS abstract)
- Work on the covariance generation for  $^{63}\text{Cu}$  and  $^{65}\text{Cu}$  using the LCOMP=2 ENDF option;

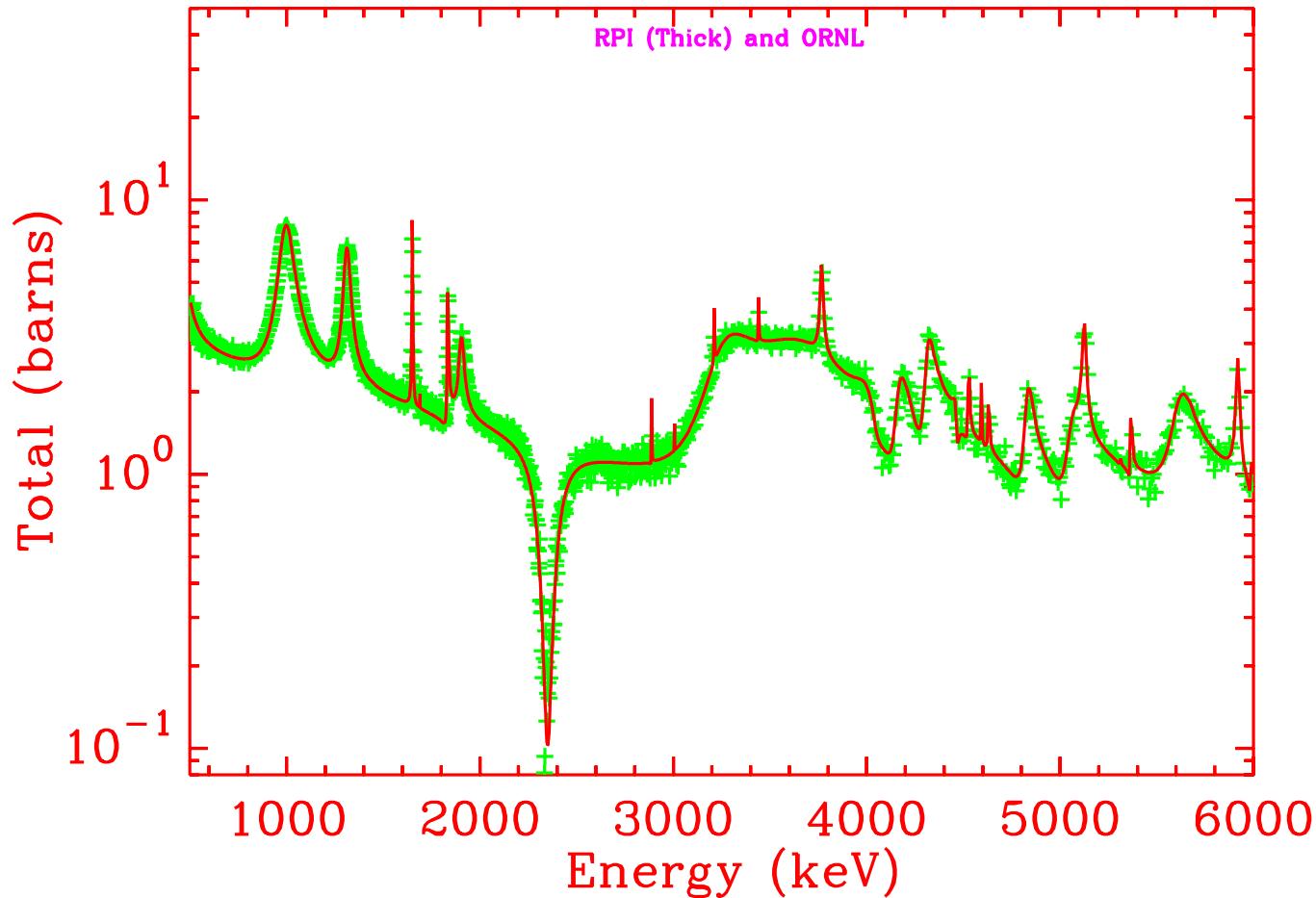
# Resonance Evaluations and deliverables

| Isotope           | Energy Range        | Resonance Covariance Evaluation | Target date for delivery the evaluation |
|-------------------|---------------------|---------------------------------|---|
| $^{16}\text{O}$   | Thermal to 6 MeV    | Yes                             | Completed                               |
| $^{239}\text{Pu}$ | Thermal to 4.0 keV  | Yes                             | Completed                               |
| $^{235}\text{U}$  | Thermal to 2.25 keV | Yes                             | Completed                               |
| $^{56}\text{Fe}$  | Thermal to 2 MeV    | Yes                             | Ongoing                                 |
| $^{54}\text{Fe}$  | Thermal to 1.5 MeV  | Yes                             | Ongoing                                 |
| $^{103}\text{Rh}$ | Thermal to 8 keV    | Yes                             | Ongoing                                 |

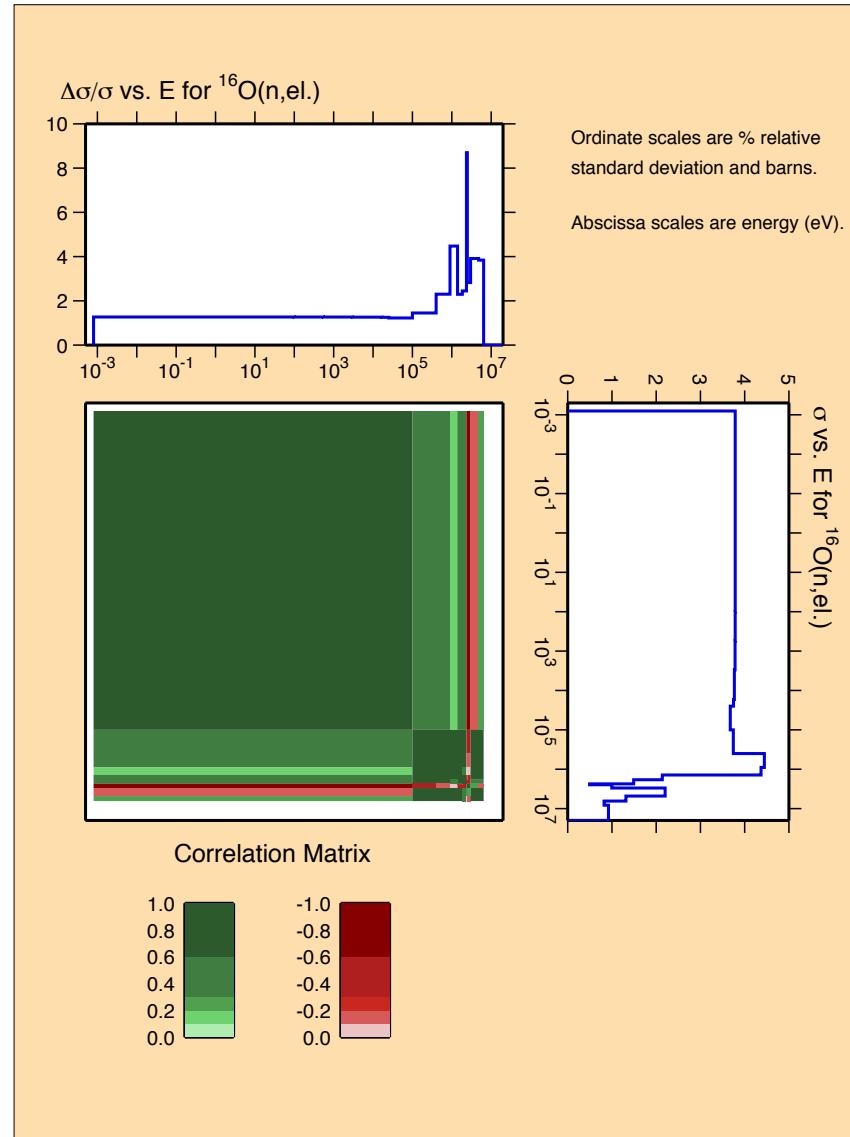
# $^{16}\text{O}$ Resonance Evaluation

- | Evaluation processed with the nuclear data processing codes NJOY, PREPRO, AMPX and GAIA;
- | The resolved resonance included in the ENDF/B-VII.1;
- | ( $n$ , total), ( $n$ ,  $n$ ), ( $n$ ,  $\gamma$ ), scattering, ( $n$ , $\alpha$ ), angular distributions are calculated from resonance parameters;
- | Resonance parameter covariance is available. Not included in the library;
- | Updated thermal scattering cross section according to the CIELO suggested value (3.765 b at 0K);
- |  $^{16}\text{O}(n, \alpha)$  data (Giorginis, et al., IRMM) and  $^{13}\text{C}(\alpha, n)$  data (Harissopoulos, et al.) give about 30% lower  $^{16}\text{O}$  ( $n$ ,  $\alpha$ ) cross section values than the Bair-Haas.

# Total cross section measurements from RPI. SAMMY comparison including resolution effects



# RRP Covariance for the Scattering Cross Section



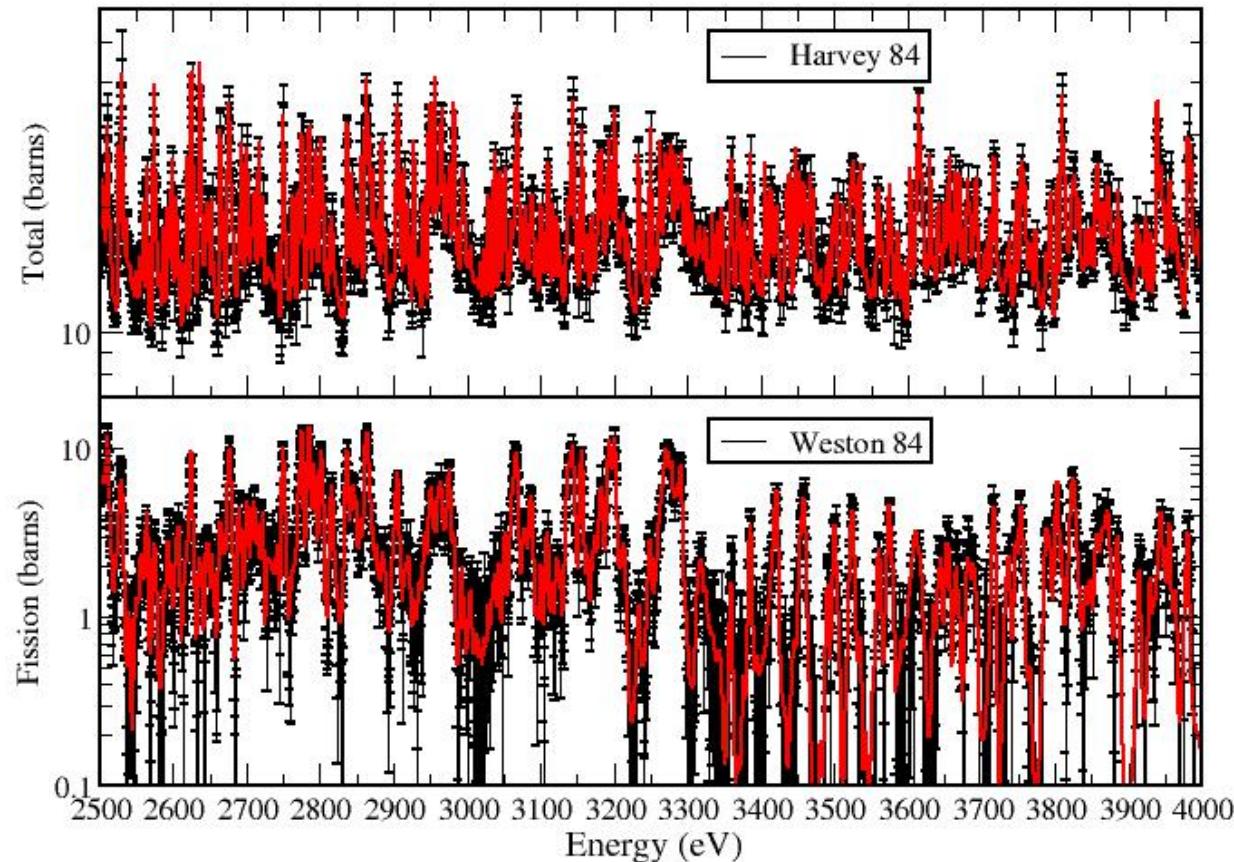
# $^{239}\text{Pu}$ evaluation work

- Extension of the resolved resonance region from 2.5 keV to 4 keV.
  - Purpose: eliminate issues with the unresolved resonance representation by using resolved resonance parameters;
- High-resolution transmission data of Harvey and fission of Weston were used in the SAMMY fitting;
- Fission cross section of Weston (1984) normalized according to the NEA-WPEC-5 subgroup on the fission of  $^{239}\text{Pu}$ . Recommendation that the fission cross section integral in 100 eV - 1000 eV is 9275 b.eV

# What is new:

- | Fitting of the capture cross section above 2 keV using data measured at LANL recently;
- | Fitting of thermal values to the standards;
- | Fitting of average fission values to the standards;
- | The evaluation indicates the fitted standard values a more consistent with benchmark results !!

# SAMMY fit to the experimental data



# $^{235}\text{U}$ evaluation work:

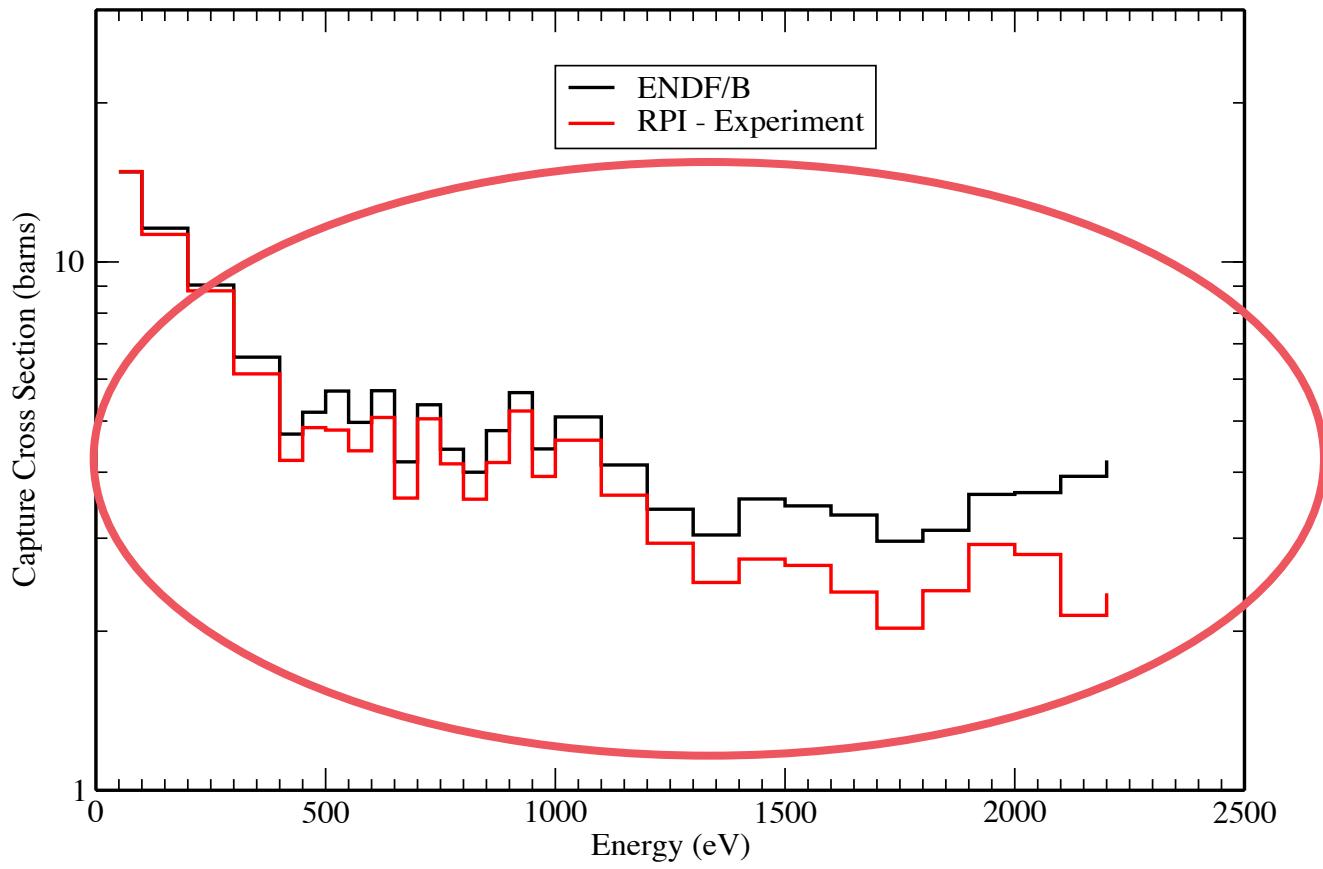
## ■ Issues:

- Overestimation of  $^{235}\text{U}$  capture cross-section in the resonance region range (0.1 to 2.25 keV).

## ■ Recommendation:

- New measurements of capture and fission cross-section in the keV region;
- Perform new resonance analysis in the 0.1 to 2.25 keV region;
- Investigate the reason for the overestimation of criticalities for some benchmarks.

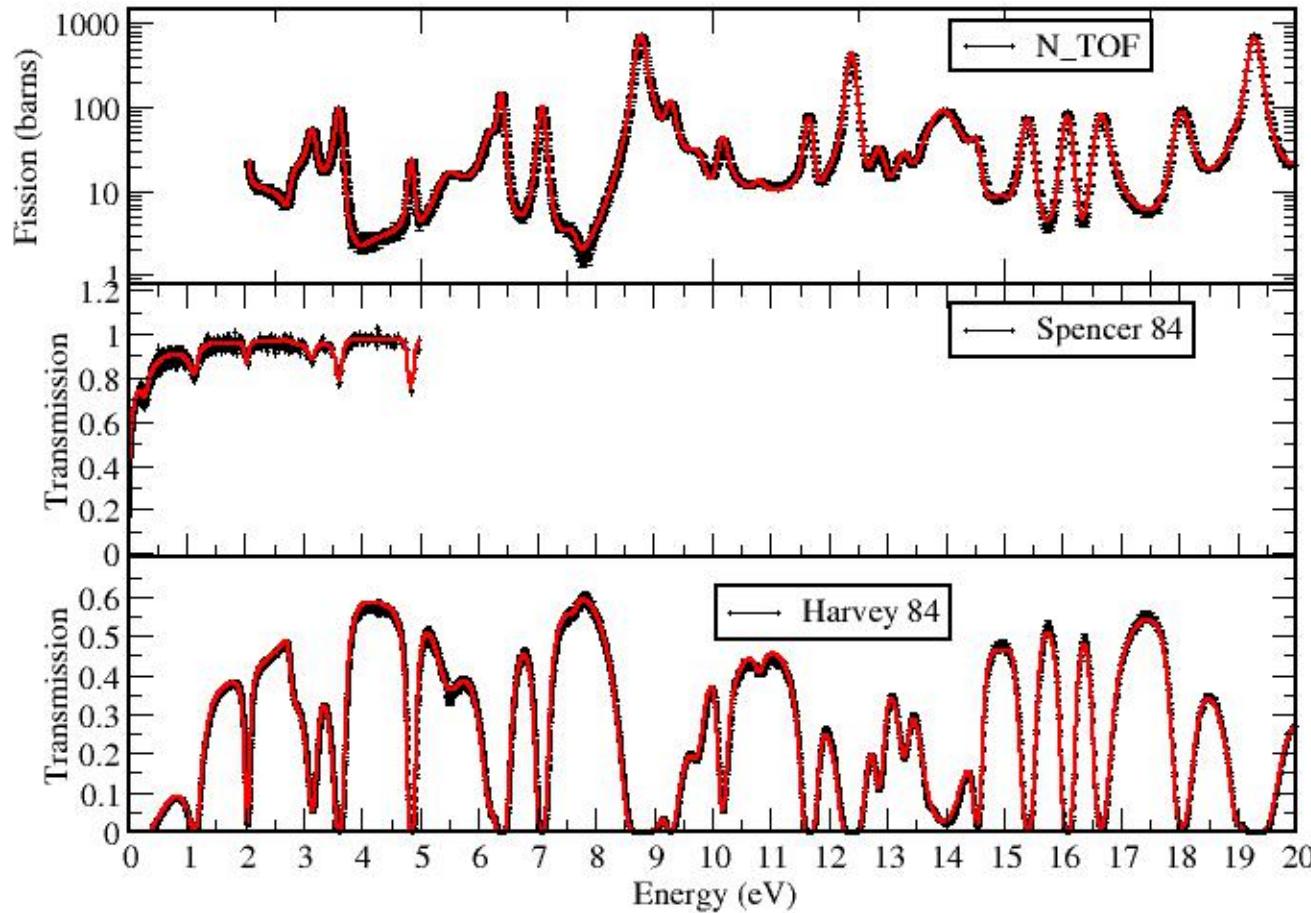
# RPI capture data and ENDF evaluation



## Selected Data

| Author                    | Energy<br>(eV)        | Data   |
|---------------------------|-----------------------|--|
| <b>Weston (ORNL/1992)</b> | <b>100.0 - 2000.0</b> | Fission at 86.5 meters   |
| <b>Moxon (ORNL/1992)</b>  | <b>0.01 - 50.0</b>    | Fission Yield  |
| <b>Gwin (ORNL/1996)</b>   | <b>0.01 - 4.0</b>     | Absorption and fission at 21.68 meters                             |
| <b>Danon (RPI/2012)</b>   | <b>100.0 – 5000</b>   | <b>Fission and capture yield at 25.56 meters<br/>(burst 15 ns)</b> |
| <b>Jandel (LANL/2012)</b> | <b>100.0 - 5000</b>   | <b>Capture at 25.45 meters<br/>(burst 125 ns)</b>                  |
| <b>N_TOF</b>              | <b>2.0 - 60</b>       | <b>Fission</b>   |

# SAMMY Fit of the Data



# $^{235}\text{U}$ Thermal Values

| Quantity                   | Standard            | B7<br>(barns) | JEFF3.2<br>(barns) | JENDL4<br>(barns) | IRSN<br>(barns) |
|----------------------------|---------------------|---------------|--------------------|-------------------|-----------------|
| $\sigma_f$<br>(barns)      | $584.380 \pm 1.030$ | 584.897       | 584.897            | 584.897           | 584.417         |
| $\sigma_\gamma$<br>(barns) | $99.304 \pm 0.725$  | 98.665        | 98.665             | 98.665            | 99.231          |
| $\sigma_s$<br>(barns)      | $14.087 \pm 0.219$  | 15.115        | 15.115             | 15.115            | 14.086          |

# $^{235}\text{U}$ Fission Integral in the Energy Range 7.8 eV to 11 eV

$$\int_{7.8 \text{ eV}}^{11 \text{ eV}} \sigma_f(E) dE$$

| $\Delta E$<br>(eV) | Standard<br>(b.eV) | B7<br>(b.eV) | JEFF3.2<br>(b.eV) | JENDL4<br>(b.eV) | IRSN<br>(b.eV) |
|--------------------|--------------------|--------------|-------------------|------------------|----------------|
| 7.8 eV - 11 eV     | $246.40 \pm 1.24$  | 241.90       | 241.90            | 241.90           | 246.31         |

# $^{235}\text{U}$ Average Fission integral

| $\Delta E$<br>(eV) | Standard<br>(barns) | B7<br>(barns) | JEFF3.2<br>(barns) | JENDL4<br>(barns) | IRSN<br>(barns) |
|--------------------|---------------------|---------------|--------------------|-------------------|-----------------|
| 100 - 200          | 21.17 (11)          | 20.33         | 20.33              | 20.29             | 20.81           |
| 200 - 300          | 20.69 (11)          | 20.62         | 20.62              | 20.66             | 21.04           |
| 300 - 400          | 13.13 (7)           | 12.81         | 12.81              | 12.81             | 13.22           |
| 400 - 500          | 13.78 (8)           | 13.33         | 13.33              | 13.31             | 13.51           |
| 500 - 600          | 15.17 (9)           | 14.89         | 14.89              | 14.73             | 15.21           |
| 600 - 700          | 11.51 (7)           | 11.26         | 11.26              | 11.13             | 11.52           |
| 700 - 800          | 11.10 (6)           | 10.89         | 10.89              | 11.06             | 11.11           |
| 800 - 900          | 8.21 (48)           | 7.98          | 7.98               | 7.93              | 8.12            |
| 900 - 1000         | 7.50 (44)           | 7.25          | 7.25               | 7.46              | 7.39            |
| 1000 - 2000        | 7.30 (40)           | 7.14          | 7.14               | 7.10              | 7.29            |

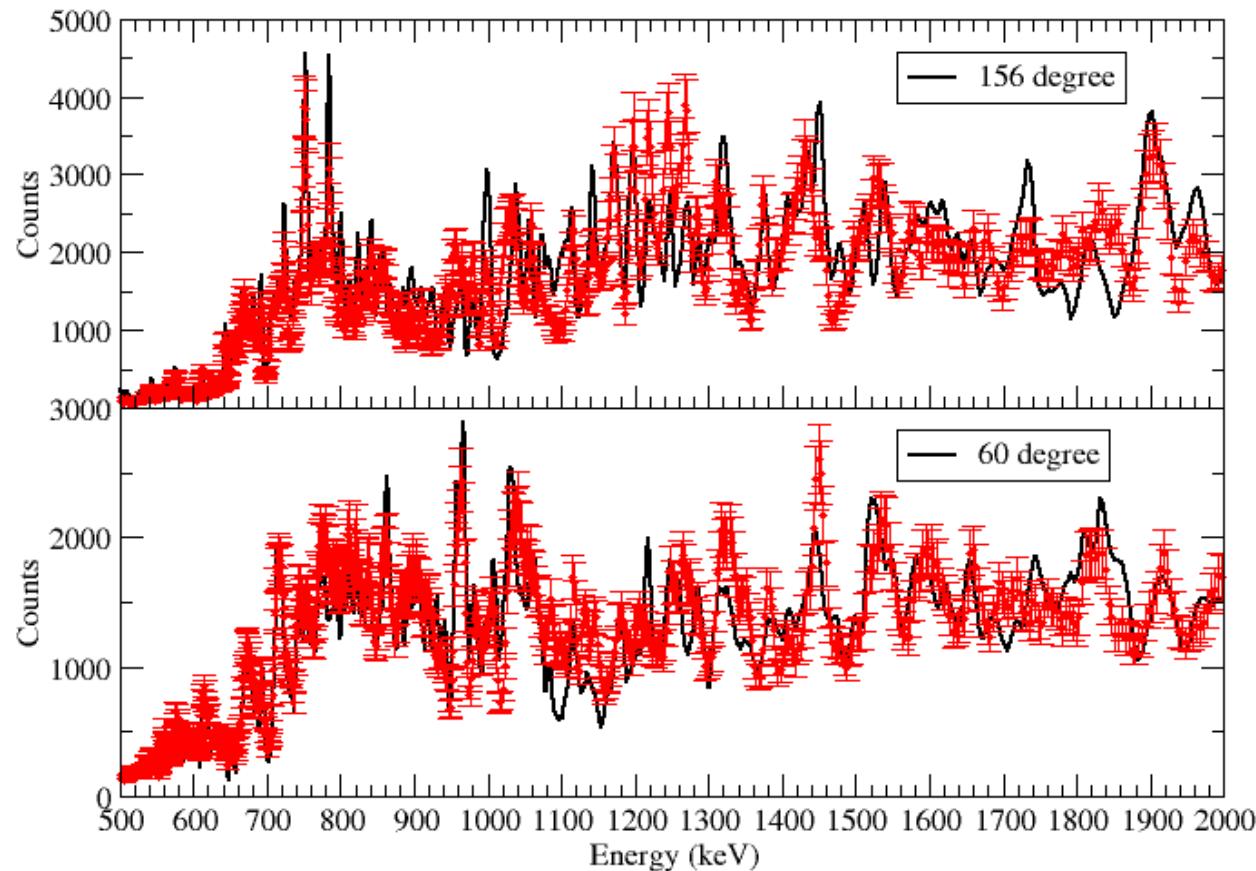
$$\langle \sigma_f \rangle = \frac{1}{E_f - E_i} \int_{E_i}^{E_f} \sigma_f(E) dE$$

# $^{56}\text{Fe}$ Evaluation

- | New high resolution transmission measurements done at the RPI extending the resonance region up to 5 MeV;
- | New inelastic cross-section measurements done at IRMM/GELINA;
- | New RPI angular scattering data (presented in this meeting);
- | Use the SAMMY/RML feature to include inelastic channel in the R-matrix analysis and evaluation;
- | Elastic and Inelastic angular data derived from resonance parameters

# SAMMY calculations and RPI Experimental data

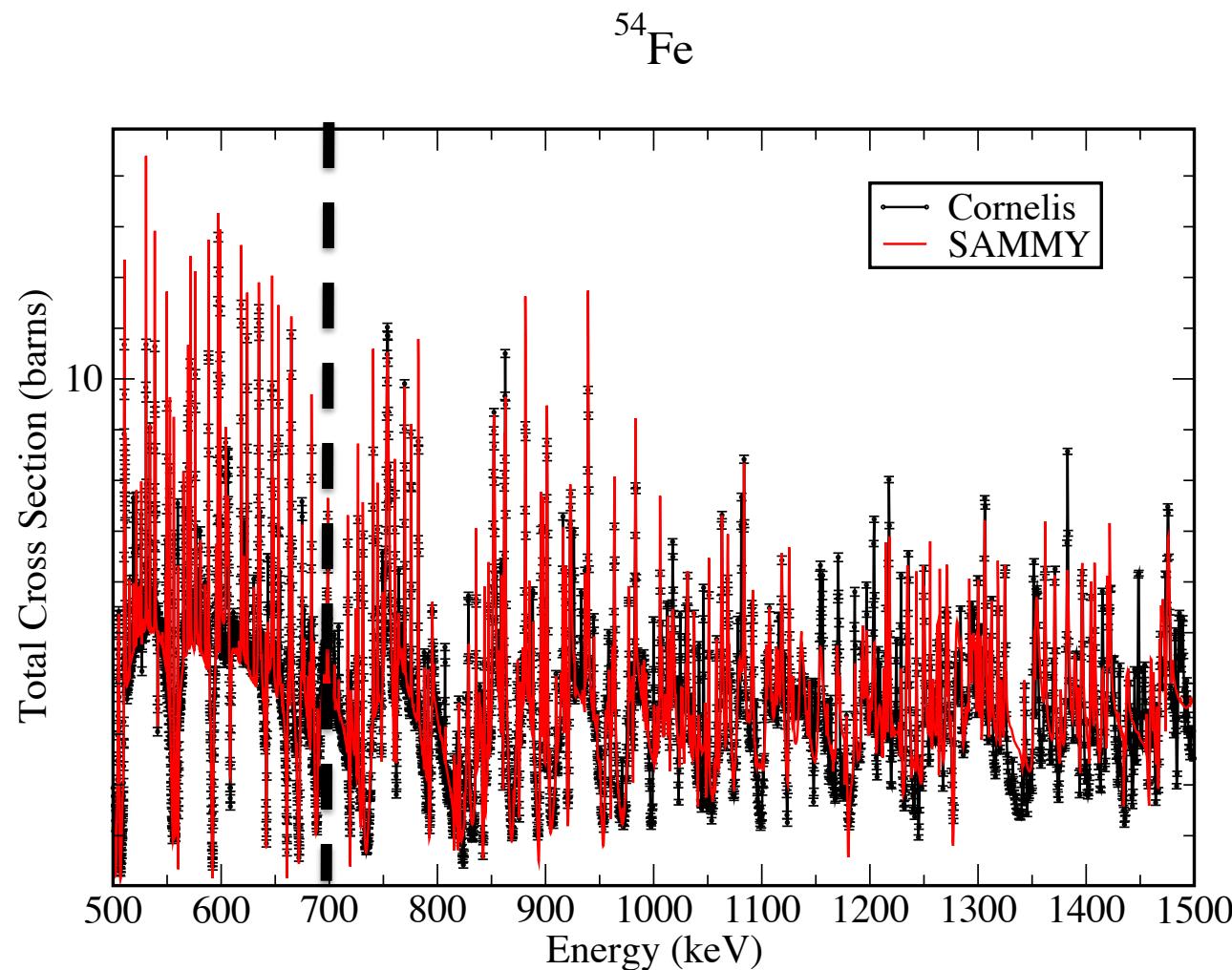
RPI Angular Data



# $^{54}\text{Fe}$ Evaluation in the Resolved Resonance

- | Natural Iron:  $^{56}\text{Fe}(91.75\%)$ ,  $^{54}\text{Fe}(5.85\%)$  and  $^{57}\text{Fe}(2.12\%)$ ;
- | Resonance region in existing nuclear data libraries is  $10^{-5}$  eV to 700 keV;
- | Transmission, capture data needed to extend the evaluation up to 2 MeV;
- | DDX Scattering cross section needed;
- | First inelastic channel opens 1.434 MeV;
- | Inelastic cross section data needed;

# $^{54}\text{Fe}$ Evaluation in the Resolved Resonance

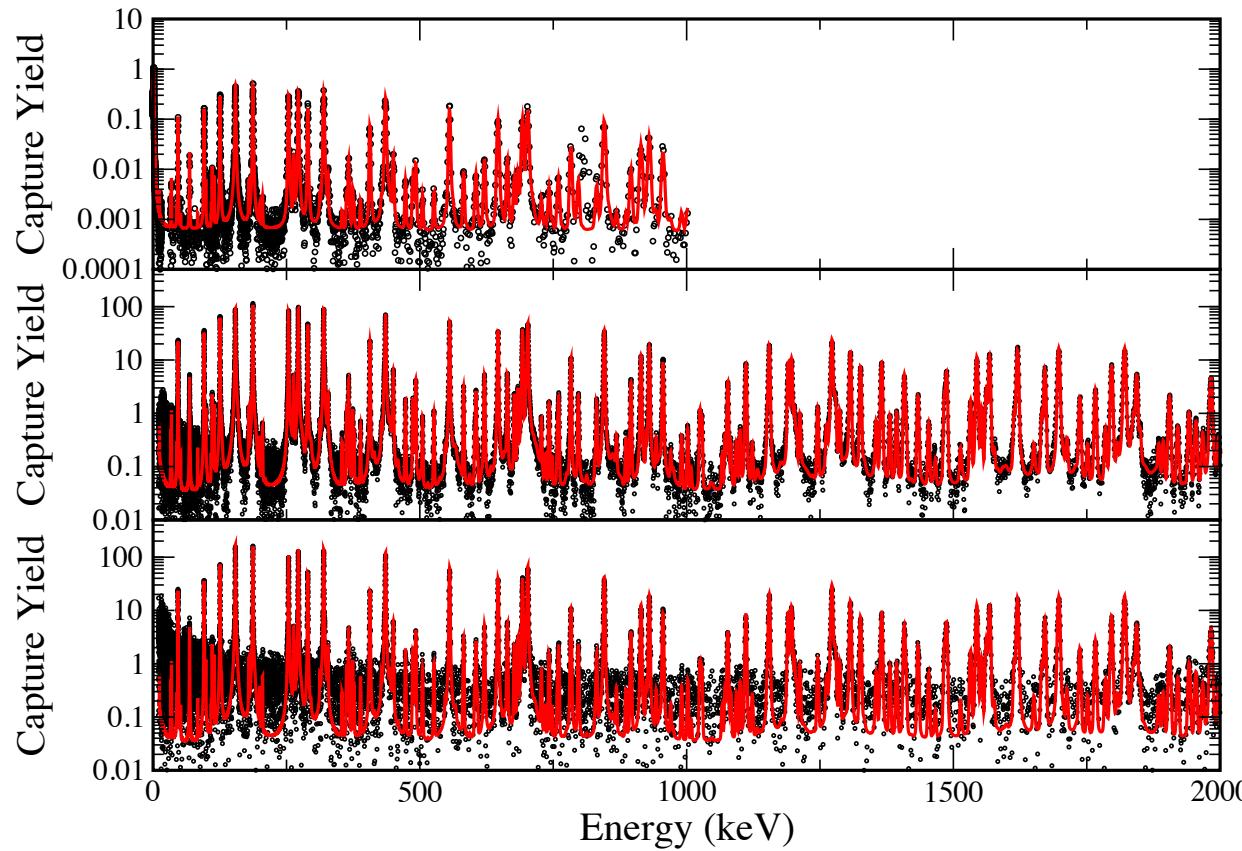


# $^{103}\text{Rh}$ Evaluation

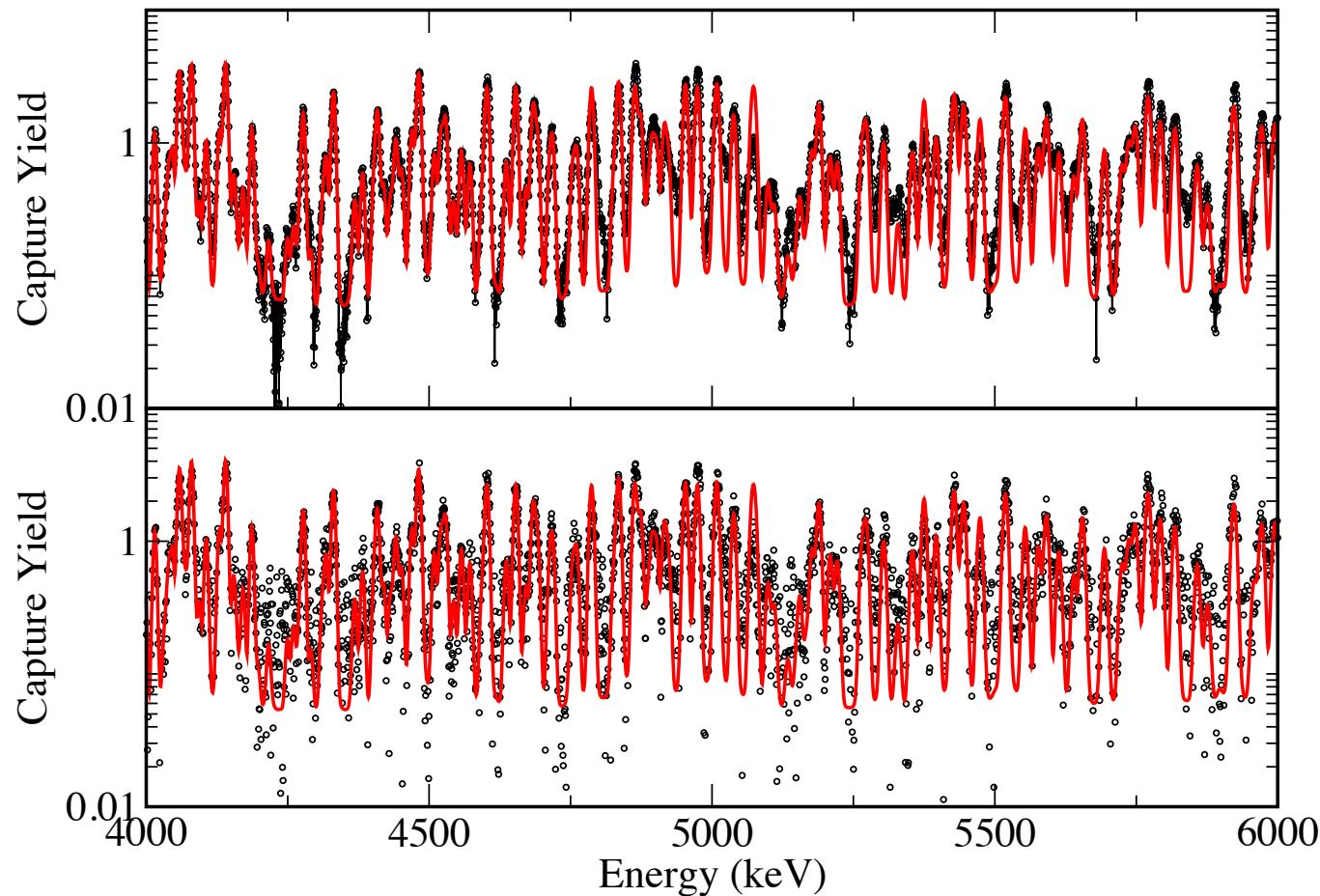
- | Resonance region in existing nuclear data libraries is 1.0-5 eV to 4 keV;
- | Transmission, capture data from GELINA used to extend the evaluation up to 8 keV;
- | There are transmission and capture data from RPI.
- | Evaluation will be released at the end of FY2016 including resonance parameters and resonance parameters covariance

# $^{103}\text{Rh}$ Evaluation in the Resolved Resonance

GELINA Data



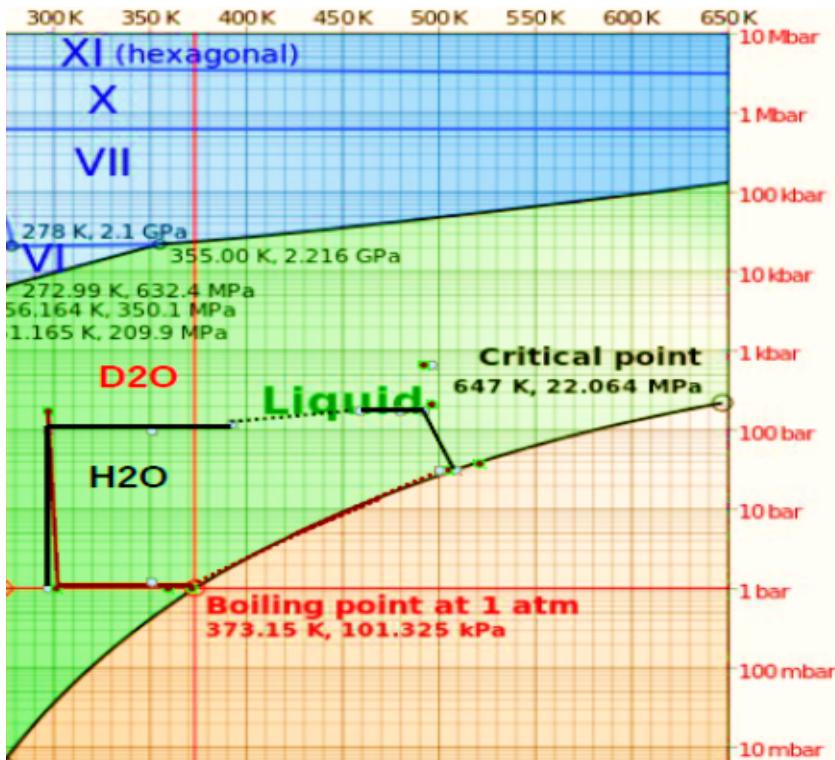
# $^{103}\text{Rh}$ Evaluation in the Resolved Resonance



# Data acquisition

## For light water:

Measurements at several temperature and pressure combinations



### Experimental conditions with IN4c

| Wavelength             | Temperature (K) | Pressure (bars) |
|------------------------|-----------------|-----------------|
| 2.4 Å°<br>Ei=14.20 meV | 300             | 1               |
|                        | 300             | 88-100          |
|                        | 350             | 115             |
|                        | 392-466         | 128-165         |
|                        | 479-485         | 172-180         |
|                        | 490-497         | 185             |
|                        | 517             | 42              |

### Experimental conditions with IN6

| Wavelength             | Temperature (K) | Pressure (bars) |
|------------------------|-----------------|-----------------|
| 5.1 Å°<br>Ei=3.145 meV | 350             | 1               |
|                        | 494             | 70              |
|                        | 494             | 600-340         |

# Concluding Remarks

- | Evaluations and validations work for isotopes listed in the NCSP Appendix D are under the schedule;
- | Issues on sample preparation for  $^{54}\text{Fe}$  for transmission data, capture and inelastic cross section measurements needs to be resolved to avoid delay in completing the evaluation task;
- | Data evaluation for  $^{54}\text{Fe}$  is needed to fully complete the  $^{56}\text{Fe}$  evaluation;
- | Final evaluation includes resonance parameters and resonance parameter covariance;
- | Continue IRSN and ORNL collaboration efforts;